Ultrastrong Stationary Double Layers in a Nondischarge Magnetoplasma

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Ultrastrong stationary double layers are generated in a magnetoplasma by simply applying potential differences between two plasma sources. The potential drop φ_D of the double layer is increased up to $e\varphi_D/T_e \simeq 2\times10^3$ (T_e is the electron temperature in eV) with no difficulties caused by gas discharge. There are always large spiky fluctuations on the low-potential tail of the double layers.

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There often appear local potential drops due to electric double layers (DL) in plasmas,[1] which belong to the class of the Bernstein-Greene-Kruskal (BGK) solutions[2] of the Vlasov equation. There is an increasing interest in the DL, because the DL accelerates charged particles and provides a mechanism for anomalous resistivity.[3] In particular, the DL has been suggested to be responsible for auroral discharges and solar flares.[4] In fact, a local potential drop was observed above the Earth's auroral region.[5] On the other hand, recent laboratory experiments[1,6-11] and computer simulations[3,12] have revealed some details of the DL.

There are, however, important factors still missed in the laboratory experiments. In several works,[6-9] electron beams were injected to generate the DL by somewhat complicated adjustment of potentials applied to grids in plasmas. Such a beam injection, however, is not always necessary for DL generation. In the experiments on stationary DL, there was no magnetic field, or ions were not sufficiently magnetized.[9-11] To discuss auroral-particle and solar-flare problems, we need to postulate a strong magnetic field which is also useful to avoid wall effects on the DL in laboratory plasmas. Moreover, most of the works were carried out in weakly ionized discharge plasmas. When the potential drop of the DL becomes comparable to the ionization potentials of the gases used, an additional discharge takes place in the plasmas, limiting the obtainable potential drop and masking some physics of the DL.[6,7] On the other hand, a local discharge [due to an electron beam or a potential applied to a probe (grid, plate)] is often responsible for DL formation.[7,11] One of the essential problems concerned with the DL is to know how a large stationary potential drop can be produced by the DL in a plasma.

This Letter reports the generation and properties of ultrastrong stationary double layers in a simple configuration under a magnetic field strong enough to magnetize ions. The DL is generated by applying a potential difference between two hot plates at which a plasma is produced by contact ionization. The stationary potential drop φ_D of the DL is successfully increased up to $e\varphi_D/T_e \simeq 2\times10^3$ (T_e is the electron temperature in eV).

The plasma produced by contact ionization of potassium vapor at two 3.5-cm-diam hot tantalum plates [source 1 (S_1) and source 2 (S_2) with separation $d = 227$ cm] is confined by an axial magnetic field $B = 2–4$ kG in a double-ended Q machine,[13] as shown in Fig. 1. The machine is operated under the electron-rich condition.[13] When S_1 and S_2 are balanced at the same potential ($\varphi_0 = 0$), ions produced at S_1 (S_2) are accelerated by an electron sheath in front of S_1 (S_2) and flow with speed

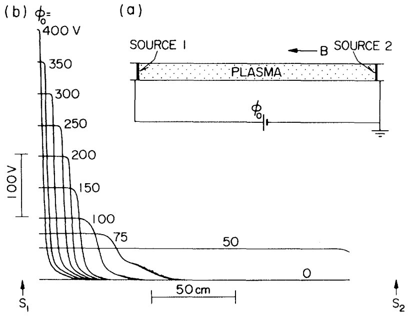

FIG. 1. (a) Schematic of experimental setup. (b) Potential distributions along the plasma column for various values of φ_0 at $N_1 = 1.1\times10^{10}$ and $N_2 = 6.8\times10^9$ cm^{-3} ($N_2/N_1 = 0.62$).

$V_0[=(1.2-1.4)(T_e/m_i)^{1/2}]$ toward S_2 (S_1). Their temperature $T_i \lesssim T_e$ ($\simeq 0.2$ eV). It is to be noted here that the most recent previous experiments on the DL were performed under the condition $T_e/T_i \gg 1$. The plasma densities N_1 and N_2, supplied by S_1 and S_2, respectively, are in the range $(0.1-1.1)\times 10^{10}$ cm^{-3} at $\varphi_0 = 0$, yielding the mean free paths between charged particles $\lambda \simeq 10-10^2$ cm. At $\varphi_0 \neq 0$, however, the local density n is smaller than N_1 and N_2 and $\lambda > 10^2$ cm in the region of the DL. The ion Larmor radius (< 0.2 cm) is much smaller than the plasma radius. The background gas pressure is 1×10^{-6} Torr. The mean free paths of charged particles with neutral particles are longer than d. To generate the DL, a potential $\varphi_0 = 0-400$ V is applied to S_1 with respect to S_2 which is grounded together with the 15.7-cm-diam stainless-steel vacuum chamber. Floating potentials of emissive probes (resolution $\simeq 1$ mm) are used to determine the plasma potentials. Other parameters are measured by Langmuir probes and grided analyzers.

Examples of axial potential distributions φ are demonstrated in Fig. 1. During the axial movement of the probe, potentials at fixed axial positions are checked to be constant. Potential drops due to the sheaths in front of S_1 and S_2 are negligibly small (less than a few volts). A potential gradient through the plasma region can also be neglected. Almost all of φ_0 appears as the potential drop of the DL, φ_D. At $\varphi_0 < 0$ the DL with opposite polarity is observed. Radially movable probes yield constant potentials across the plasma, which mean one-dimensional configurations of our DL in the plasma. The DL moves toward S_1 with an increase in φ_0. The maximum potential drop, $e\varphi_D/T_e \simeq 2\times 10^3$, is larger than the previous experimental results by two or three orders of magnitude. Its width L is in the range (200–600)λ_D (λ_D is the Debye length around the DL), and $\gamma\ [=(\lambda_D/L)(e\varphi_D/T_e)^{1/2}] \simeq 0.07-0.22$ is close to the value ($\gamma \simeq 0.17$) predicted by Joyce and Hubbard[12] in their computer simulation.

The potential slope of the sharp DL (at $\varphi_0 \gtrsim 100$ V) increases with an increase in N_1 (N_2) on the high- (low-) potential side (with respect to the center of the DL). The DL position is controlled by changing the ratio N_2/N_1. When it is increased, the DL approaches S_1. In order to see the DL with smaller values of φ_D, N_2/N_1 is increased in Fig. 2, where the DL is found in the range $e\varphi_D/T_e \simeq 25-700$ [the DL with $e\varphi_D/T_e \simeq 1-25$ (not shown) is also observed]. The width of the DL, however, does not decrease with a decrease in φ_0 at relatively small values of φ_0, contradicting the ideal theory.[14] Measurements of potential fluctuation $\tilde{\varphi}$ show large positive spkies with frequency 1–10 kHz on the low-potential tail of the DL. They are accompanied by positive spikes in the electron current passing through the plasma. The ratio $\tilde{\varphi}/\varphi_D$ (less than or approximately equal to a few tens of percent) increases as φ_0 is decreased. These fluctuations are responsible for the apparent broader width of the weaker DL, because the measured profiles are averaged over the fluctuations. The current I_0 through the plasma and its fluctuation $\tilde{I}$ are plotted against φ_0, also in Fig. 2. An initial increase in I_0 is followed by an increase in $\tilde{I}$. An abrupt decrease in I_0, with subsequent saturation of $\tilde{I}$, around $\varphi_0 = 1.5$ V corresponds to the DL generation. After some characteristic changes, there appears a jump of $\tilde{I}$ where the sharp DL is formed near S_1. In the relatively flat region of $\tilde{I}$ and I_0 for $\varphi_0 \gtrsim 100$ V, there is no appreciable change of the DL shape except that there are an increase in φ_D and a small change of the position.

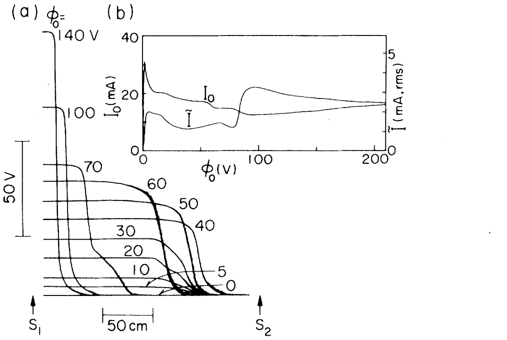

FIG. 2. (a) Potential distributions and (b) total current I_0 passing through the plasma column and its fluctuation $\tilde{I}$ against φ_0 at $N_1 = 6.4\times 10^9$ and $N_2 = 5.1\times 10^9$ cm^{-3} ($N_2/N_1 = 0.80$).

The electron beam produced by the DL broadens within a distance of 60 cm beyond the DL, as shown in Fig. 3. This broadening is ascribed to the generation of electron plasma waves in a bounded magnetoplasma. The phenomena are observed in the wide range of φ_0(greater than or approximately equal to a few volts). The ion beam observed on the low-potential side is also broadened near the DL. Profiles of electron and ion currents, j_e and j_i, picked up by the Langmuir probe are also shown in Fig. 3, where the beam currents, j_{eb} and j_{ib}, are distinguished. The grided analyzer yields $j_{eb}/j_{ib} \simeq 200$, showing a rough agreement with the Langmuir condition,[14]

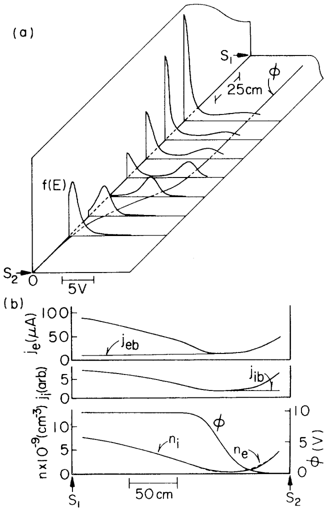

FIG. 3. Spatial changes of (a) electron energy distribution function $f(E)$, (b) currents picked up by the Langmuir probe (0.13 mm in diameter and 3 mm long) and corresponding densities, together with potential profile φ, at $\varphi_0 = 10$ V. Electron saturation current j_e is given by a turning point of the electron current on the probe characteristics. There is another turning point of the electron current in the high-potential region of the DL, which is due to electron-beam current j_{eb}. A profile of ion current j_i is given by the probe at -20 V with respect to the potential yielding j_e. Ion-beam current j_{ib} corresponds to the ion flow passing through the DL toward S_2. Electron and ion densities, n_e and n_i, are obtained from j_e and j_j ($n_e = n_i$ is assumed at the start of traces).

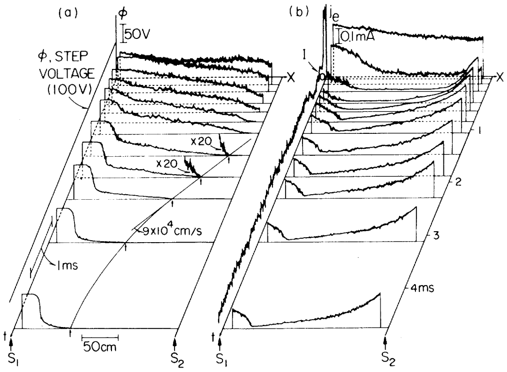

FIG. 4. Spatial profiles of (a) potential φ and (b) electron current j_e at time $t > 0$ when a step voltage φ_0(= 100 V) is applied to S_1 at $t = 0$. In this case, j_e is picked up by the probe biased at 150 V with respect to the ground potential. I is the current passing through the plasma column.

$j_{eb}/j_{ib} = (m_i/m_e)^{1/2}$ ($\simeq 270$). The densities, n_e and n_i, decrease gradually toward the DL, where we find a small charge separation.

A process of DL formation is shown in Fig. 4. Just after the application of a step potential φ_0 to S_1 at time $t = 0$, the potential penetrates into the plasma (j_e is almost constant), generating fluctuations in both φ and j_e. Then there appears a gentle potential slope between S_1 and S_2, which reflects the electrons and accelerates the ions supplied by S_1. Since these ions (accelerated by the electron sheath in front of S_1) satisfy the Bohm criterion,[15] we can expect a subsequent start of abrupt drops in both φ and j_e near S_1. In the central region, these decreases are further enhanced. In the flat region of j_e at $t = 0.3$–1.3 ms, j_e has a value which is caused only by the beam electrons flowing toward S_1. The current, however, is much smaller than the initial electron current supplied by S_2. This current limitation suggests the existence of a negative potential dip ($\simeq T_e$) formed near S_2. The flat region of j_e is gradually filled up by the plasma supplied by S_2. On each potential profile at $t \gtrsim 1.4$ ms can be found a special point (shown by a small arrow) where φ shows a small jump with fluctuation. This point moves toward S_1 with V_0 [$= 1.28(T_e/m_i)^{1/2}$], but is slowed down and finally stops. Detailed observations of spiky fluctuations suggest that this point fluctuates back and forth on the low-potential tail of the DL in the steady-state measurements.[16]

In this work, a quite simple method is established for the DL generation in a simple configuration. The stationary DL with potential drop in the range $e\varphi_D/T_e \simeq 1$ (weak DL)–2×10^3 (ultrastrong DL) is generated with no difficulties caused by gas discharge in a magnetoplasma. For a larger value of N_1, the DL with the larger potential drop is realized in a plasma, although detailed measurements are not made to protect the measuring circuit. On the other hand, double-layer-like potential drops are observed even for $e\varphi_0/T_e \lesssim 1$. It is worthwhile examining our results in connection with investigations of current-driven instabilities, because they were performed by using the same configuration in a number of experiments[17] where no local potential drop along the plasma column was taken into account. Recently, Stenzel *et al.*[18] investigated the V-shaped double layers which were generated by ion-beam reflection from a positively biased target under a converging magnetic field, although B is not strong enough to magnetize ions throughout the experimental region. We can also generate the DL in a mirror configuration of magnetic field as an extension of our work.

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Filamentary Collapse in Electron-Beam Plasmas

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Observations of a form of three-dimensional turbulence, which occurs in beam-plasma interactions, are described. Large amplitude, beam driven instabilities in both the oblique electron plasma and electron-cyclotron modes are shown to collapse into thin, magnetic field aligned filaments, and to exhibit a variety of modulation time scales characteristic of both electron and ion modes in the system. On the largest time scales, associated density depletions are observed.

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In recent years there has been considerable interest in the nonlinear evolution of large-amplitude electron waves in plasmas and in the processes leading to self modulation and formation of solitary or collapsed wave field structures.[1-11] To date, experiments have been carried out in either magnetic-field-free systems, or in very strongly magnetized plasmas leading to quasi-one-dimensional effects.[1-5]

As with some other experiments, in those described here, large-amplitude waves resulting from a beam-plasma interaction form the high-frequency pump for the system. The beam is unmodulated in order to avoid complications arising from the insertion of wave launching antennae and, significantly, because it is of small radius, the unstable waves are rather oblique ($K_\perp > K_\parallel$) to the axial magnetic field, resulting in a quasitransverse pump wave field.

The characteristics of the apparatus are as follows: A thin (0.75-cm-diam) electron beam (current variable up to 7 mA, energy variable in range 150–250 eV) is injected axially from one end of a 10-cm-diam, 150-cm-long glass vessel immersed in a dc axial magnetic field. The beam-produced argon plasma (typical pressure $\sim 10^{-4}$